An overview of the Compensated Earth-Moon-Earth Laser Link (CEMERLL) experiment

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ABSTRACT

Adaptive optics can mitigate the turbulence-induced wavefront distortions that limit the minimum practical beam divergence in a ground-to-space optical link, and enable high intensity laser beam propagation through the atmosphere. The CEMERLL experiment will usc laser guide star adaptive optics to transmit a near-r+iiffraction-limited laser beam from the Starfire Optical Range to the Apollo lunar retro-reflectors. The experiment will validate theoretical models that predict the effect of atmospheric turbulence on uncompensated and compensated laser beam propagation, and explore strategies to compensate for atmosphere-induced wavefront tilt not corrected for by laser guide star adaptive optics.

I. INTRODUCTION

With the thrust in solar exploration towards micro and mini spacecraft, a small, low mass, low power consumption optical communications package is an attractive alternative to the current large RF communications systems, Yet, to effect communications between the deep-space probe and the Earth, the spacecraft must "know" the Earth's location and compute the requisite point-ahead angle at which to transmit the narrow downlink signal. Approaches for generating a point-ahead reference beacon range from using Earth shine to uplinking an intense laser beam. At large ranges, the Sun-probe-Earth (SPE) angle is always small, and the proximity of the Sun to Earth in the detector field of view (fov) will degrade the determination of the point-ahead angle. The Earth is a useful beacon for spacecraft at intermediate ranges—e.g., spacecraft at Mars---when the Sun-Earth-probe (SEP) angles arc greater than 10°. However, its usefulness degrades as the SEP approaches 180°. At close ranges, the Earth image exceeds the detector's fov, and using a section of the Earth's image to determine the required point-ahead will require complex signal processing on board the spacecraft.

The alternative approach of uplinking an intense laser beacon is applicable at all distances and at SEP angles >10°. The spectral purity of the laser emission enables the usc of matching narrow-band interference filters and/or atomic line filters to reduce signal contamination caused by background light from the Sun and planets. Yet, laser beam uplinks arc plagued by beam wander and beam breakup caused by atmospheric turbulence. in the past, these effects were mitigated by broadening the beam to divergences comparable to, or greater than, the mean atmospheric seeing—about 10 microrad [1,2]. For a near IR beam transmitted from a nominal 1-m aperture., such a strategy imposes a 20 dB penalty on the intensity delivered to the target, This was the approach used in the GOPEX uplink [2], where beams 60 to 11() m icrorad wide were propagated to the Gal ileo spacecraft to compensate for telescope pointing errors and atmosphere-induced beam broadening and tilt.

Recently declassified laser guide star adaptive optics (LGS-AO) techniques, however, can be used to mitigate the effects of wavefront distortion on ground-to-space laser links [3,4,5]. LGS-AO can compensate for turbulence-induced beam broadening [6], and enable propagation of near-diffraction-limi[cd beams through the atmosphere. Reduced uplink beam divergence translates into a brighter beacon uplink or greater link margin. The CEMERLL experiment will explore the applicabilit y of LGS-AO to deep-space optical communications,

CEMERLL is a joint JPL/Philips Laboratories experiment scheduled for March through May 1994. An LGS-AO compensated Nd:YAG laser scoring beam is propagated from the Air Force Philips Laboratories' 1.5-m telescope at the Starfire Optical Range (SOR) in Albuquerque to the lunar retro-reflectors. The retro-reflected signal is detected at the newly installed 3.5-m telescope located approximately 100 m away; see Figure 1. The experiment has three objectives, viz.:

1. Validate the. theoretical predictions for signal enhancement achieved for compensated laser beam transmission through clear-air turbulence.

2. Evaluate strategies to compensate for atmospheric tilt.

3. Measure statistics of atmospheric propagation at 532 nm and 1064 nm and compare with theoretical predictions.

This paper is an overview of the CEMERLL experiment. The theoretical model for the link is presented in Section II, and the experimental arrangement and tilt-compensation strategies arc described in Section 111. The conclusion is given in Section IV, with acknowledgments and references given in Sections V-and V], respectively.

II. THE THEORETICAL MODEL

Turbulence randomizes the phase of an optical beam propagating through the atmosphere. For an uncorrected uplink beam, the intensity distribution at the-top of the atmosphere is a randomly tilting, time varying, speckle pattern, with spatial and temporal distributions correlated to the strength of and variations in the atmospheric turbulence. For each uplink pulse, the intensity distribution at the top of the atmosphere can be modeled as the superposition of randomly distorted wavefronts resulting from scatterers in the beam path. When averaged over a large number of pulses, the fluctuations in the detected signal strength can be described by a probability density function (pdf) parameterized in terms of measurable atmospheric quantities. The fluctuations arc best described by a log-normal distribution for propagation through weak turbulence, and by an exponential distribution for propagation through strong turbulence [7]. Both distributions were used by Levine et al. to analyze the GOPEX data [8]; the large variations in winter weather over the eight day period resulted in both strong and weak turbulence at the transmitter sites, For the uncompensated CEMERLL uplink, the. more general 1-K distribution is used [9], The I-K characterizes the statistics of the optical channel for a wide variety of turbulence conditions, approaching unity for weak turbulence and an exponential distribution in the strong turbulence limit.

The Nakagami distribution forms the basis of the non-tilt-corrected compensated uplink model. Here, the uplink pdf is a combination of the. uplink pdf for a distortion.free wavefront combined with a jitter pdf to simulate tilt. LGS-AO corrects for the higher order optical wavefront distortions, significantly reducing the speckle in the intensity distribution. Yet, because LGS-AO does not compensate for tilt, the k-vector of the transmitted beam randomly varies about the mean pointing direction with a variance determined by atmospheric turbulence. For the tilt-corrected uplink, the jitter pdf is set to unity and the unconditioned Nakagami distribution is used to describe the uplink statistics.

Figure 2 is a plot of the pdf's for the compensated and uncompensated uplinks at 1064 nm. The compensation here does not include tilt. An atmospheric coherence cell size of r. = 7 cm [1 0] was used in the.se calculations. The figure shows that the most probable signal return for the compensated uplink is greater than that of the uncompensated transmission, and that LGS-AO compensation results in a significantly larger number of high intensity retro-reflected signals than does the uncompensated uplink. This is evidenced by the long tail of the distribution for the compensated uplink. However, the figure also shows that the maximum probability of detecting the return signal is less for compensated beam propagation than for the. uncompensated uplink. This is consistent with our expectation that the jitter in the narrow compensated beam will cause the beam to flicker On and off the target more frequently than the atmosphere-broadened uncompensated beam will. The mean number of photons expected from the Apollo 15 retro-reflector array is given in l'able 1 for the compensated and uncompensated uplinks. The uplink beam is nominally 2 microrad wide at the telescope, with the uncompensated beam broadened to 10 microrad by turbulence. The predictions in the table correspond well with previous lunar retro-reflect ion measurements [11], which were obtained by using a 10 to 15 J per pulse doubled Nd:Glass laser uplink. In this experiment, the retro-reflected returns ranged from 5 to 30 photons collected by a 1.5-m receiver.

Table 1. Average number of retro-reflected photons expected at the 3.5-m telescope from the Apollo 15 array.

λ, μm	Uncompensated	Compensated	Compensated + tilt correction
0.532	36	51	912
1.064	294	465	15,720

The statistics of the signal detected at the. 3.5-m receiver represent the statistics of the uplink, the downlink, and the photon detection processes. To recover the uplink statistics from the two-way--link CEMERLL experiment, the effects of the atmosphere on the downlink and those of gain dispersion in the detection process must be deconvolved from the measured statistics.

Aperture averaging over the large 3.5-m primary mitigates scintillation-induced fades in the detected downlink. The atmosphere, therefore, only attenuates the retro-reflected signal (i.e., reduces the mean number of collected photons), and dots not alter the. distribution of the uplink pdf. In addition, gain dispersion in the detection process is insignificant at the high retro-reflected- photon levels expected. The measured signal statistics will therefore mirror the statistics of the received photons [9]. Because neither detector nonlinearities nor atmospheric effects on the downlink affect the. uplink pdf, the statistics measured at the receiver reflect the statistics of the uplink beam.

111, THE EXPERIMENT

The experiment will be performed in two phases: propagate, uncompensated and non-tilt-corrected compensated diffraction-limited divergent laser beams to the lunar retro-reflectors and compare the statistics of the return signals, and (ii) usc light from an exoatmospheric beacon to compensate for atmosphere-induced wavefront tilt. Table 1 shows that at the 1064-nm wavelength, LGS-AO compensation increases the average signal return by 2 dB, and by an additional 15 dB when combined with tilt correction,

1. The Transmitter

The uplink transmitter is a Q-switched Quanta-Ray model DCR-2A Nd:YAG laser coudé-coupled to the SOR 1.5-m elevation-over-~,irnuth telescope. The Nd:YAG operates at a 20 Hz repetition rate, and emits 10 ns wide pulses of 1.5 J and 0.35 J at the. fundamental and frequency doubled Nd:YAG wavelengths, respectively. Intracavity beam-forming optics generate a flat-top laser output (Figure 3), and relay optics and other optical elements (Figure 4) direct the laser output to the telescope.

The laser guide star is generated from Rayleigh backscatter in a 2.4 km-long range gate around the 10-km focus of the 200 W (40 mJ, 50 ns wide pulses at 5 KHz repetition rate,) copper vapor laser (CVL). The CVL beam is brought into the optical train from below the optical bench (see Figure 4), and it reflects off the aperture sharing element, which in turn directs it to the coalignment beam-splitter. Powered optics precondition the scoring and LGS beams so that they propagate through the optical train with wavefront curvatures that bring the CVL to a focus in the atmosphere and transmit the near-diffraction-lin~itcd Nd:YAG beam to the lunar rctro-reflectors. For the 532-nm transmission, a doubled YAG notch transmission beam-splitlcr replaces the long-wave-pass beam-splitter. This beam-splitter is a big})-dan]agc-threshold element with greater than 98.5% transmission at 532 nm and in cxccss of 99% reflection at the 51 0.6-nm and 578.2-nm CVL lines (Figure 5). It enables ready coalignment of the guide star and the scoring beams.

Higher order wavefront distortions detected across the 1.5-m aperture are measured by the wavefront sensor (WFS) and compensated for at the deformable mirror (DM). A WYKO interferometer continuous] y measures the. DM. The. point-ahead angle--4,8 microrad for the lunar uplink– and tilt compensation arc implemented at the. fast steering mirror (FSM).

2. The Targets

The targets arc the retro-reflector arrays deployed during the Apollo 11, 14 and 15 lunar missions. These rctro-reflectors, located at Tranquility base, at Fra Mauro, and near Hadley Rille, arc routine.]y used for laser lunar ranging [1 1,12,1 3]. The Apollo 11 and 14 arrays consist of 100 solid fused silica corner reflectors, each 3.8-cm in diameter, installed in a square aluminum panel (68 cm x 68 cm, Apollo 11; 64 cm x 64 cm, Apollo 14). The large Apollo 15 array contains three hundred comer cubes hexagonally close-packed in a 105 cm x 65 cm rectangular panel [14].

3. Tilt Compensation

Wave.front variation, including tilt, is measured and corrected at the 1.5-m transmitting aperture. Four PMT's and a pyramid mirror arc used to measure the atmospheric tilt at 532 nm. A SSPM (solid-state photomultiplier) in quad cell configuration measures the wavefront tilt at 1064 nm. Two tilt-compensation strategies will be evaluated. In both cases, tilt-compensation is effected at the FSM,

The first approach uscs sunlight reflected from a lunar feature in the vicinity of the rctro-reflectors as a beacon to c1osc the tip-tilt loop. The laser guide. star is used to correct for the higher order distortions, and to enable a well-corrcctcd image of a lunar feature to be tracked. The increased intensity in the corrected lunar image enables closing the tip-tilt loop around the FSM. This approach simulates using light reflected from a feature on a planet or its moon as a beacon to measure atmospheric tilt and thus enable propagation of a tilt-corrected beacon to a dczp-s.pace probe orbiting the planet or moon.

Figure 6 consists of two 100 millisecond exposures of lunar features, onc taken with and the other without the LGS-AO compensation loop closed. The images, taken through an optical filter centered at 700 nm, represent preliminary results in the first step toward implementing the combine.d LGS-AO and tilt-compensation strategy, A comparison of the two frames shows the significant improvement in image resolution when the LGS-AO loop is closed. Since these pictures were, taken, reductions in the electronics noise of the fast-steering mirror have resulted in further improvements in image quality.

The second approach measures the full-aperture tilt during the return pulse at the 1. S-m telescope and adjusts the FSM prior to transmission of the next pulse. This simulates using the optical communications signal as a beacon to enable propagation of a tilt-compensated **uplink.** The tilt error accumulated as the rctro-reflected beam propagates through the atmosphere is measured and corrected for on the next outgoing pulse. It is estimated that a minimum SNR of 2, or approximately 4 photons per measurement (for a noise-free detector), is needed to close the loop [15].

4. The Receiver

The retro-reflected beam is detected at a 3.5-m telescope, located approximately 100 m from **the** transmitter. The large collecting aperture gives 7 dB greater light collection than the 1.5-m tclc.scope, and yields a greater dynamic range in the photon **collection statistics,** A **noise-fre~ Rockwell** Science Center SSPM (8% quantum **efficiency at 1.06 mm and** greater than 30% quantum efficiency at 532 nm) cooled to liquid He temperatures is used to detect the retro-reflected signal.

IV. CONCLUSION

The CEMERLL experiment has been described. The experiment will be performed at the **SOR** facilities of the. Air Force Philips Laboratories, and will evaluate. the. applicability of LGS-AO to dccj)-space optical communications. A laser guide star generated by focussing a copper vapor laser 10 km above the transmitter site will be used to achieve wavefront compensation of a Nd:YAG scoring beam, Both 532-nm and 1064-nm pulses will be transmitted to the Apollo 11, 14 and 15 retro-reflectors, and the return signal will be dctcctcd at a 3.5-m telescope. The measured signal statistics will be compared with theoretical predictions in terms of the pdf's, and strategies will be implemented to achieve tilt-compensation of the LGS-AO compensated scoring beam. These strategies have been described, and the, results will be compared to the predicted signal enhancement.

V. ACKNOWLEDGMENTS

The author acknowledges the contributions of R. Fugate, B. M. Levine, K. Kiasaleh and J. R. Lesh to this manuscript, and the support given to the CEMERLL project by B. Hogge, M. Shao, and X. X. Newhall. The author also acknowledges the support of the SOR team members.

The work described in this paper was performed by the Jet Propulsion laboratory, California Institute of Technology, under a contract with the National Aeronautics and Space Administration.

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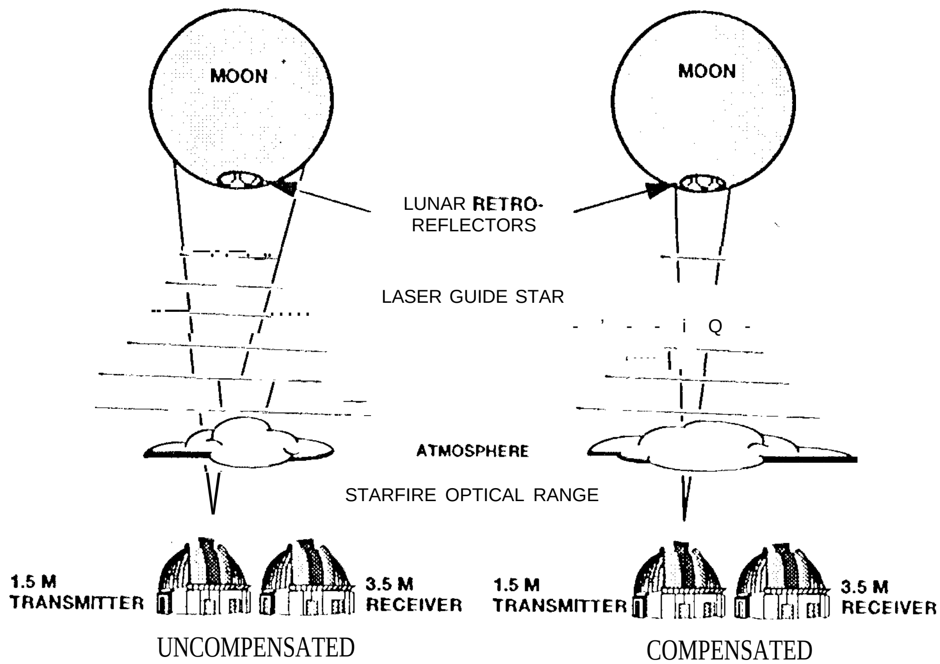

Figure 1. The CEMERLL uplink. Near-diffraction-limited beams are propagated to the lunar **retro-reflectors from the 1.5-m SOR telescope, and the retro-reflected return is detected at the 3.5-m telescope, approximately 100 m away. The uplink depicted on the left is uncompensated for turbulence, and atmospheric effects expand the beam to the width of the atmospheric seeing. Depicted on the right is the use of liner guide star adaptive optics to compensate for higher order turbulence, which enables the propagation of a narrow beam to the target.**

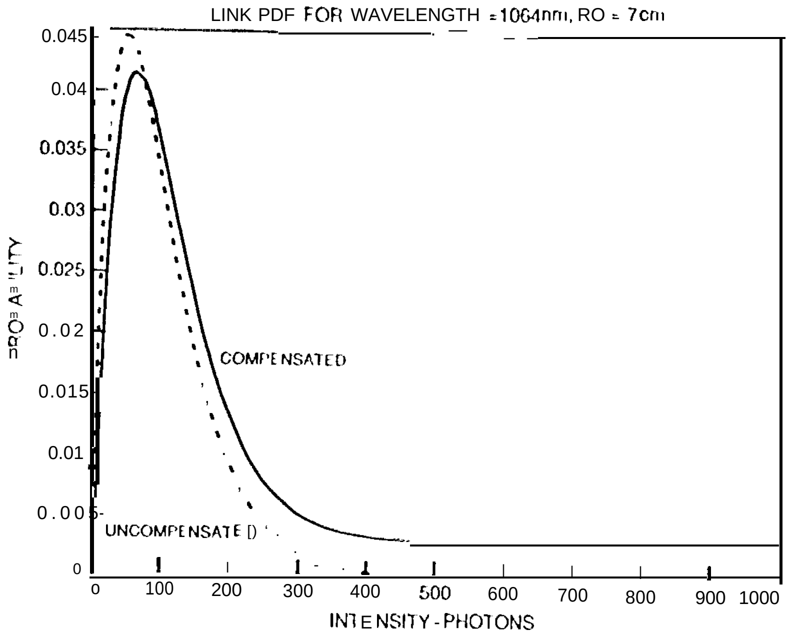

Figure 2. The **pdf for the 1064-nm laser uplink to the lunar retro-reflectors. Although the most probable signal return is almost the same for both the compensated and uncompensated uplinks, a much greater number of high intensity returns will be observed for the compensated uplink. This is evidenced by the long tail of the compensated uplink pdf.**

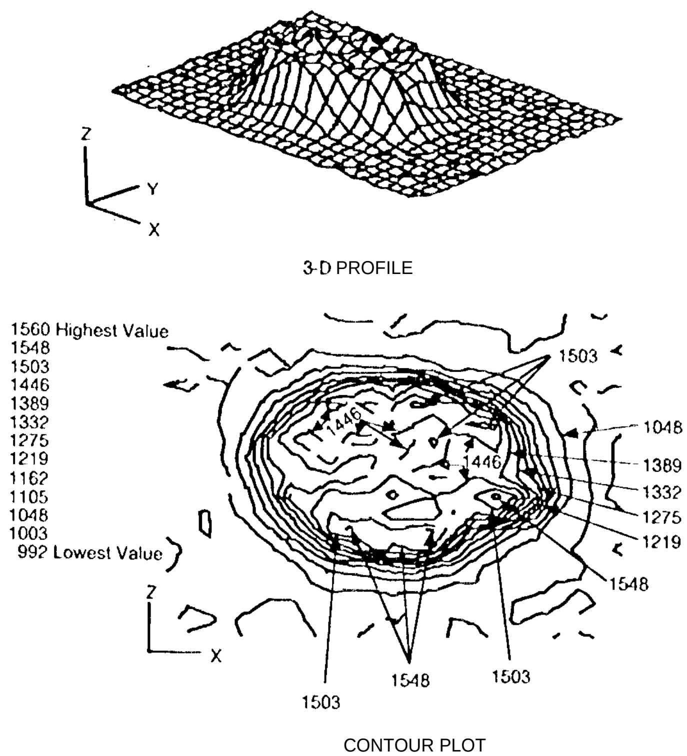

Figure 3. Beam-forming optics in the Nd:YAG cavity generate a top-hat beam profile, The beam profile after frequency doubling to S32 nm is similar to that of the 1064-nm fundamental.

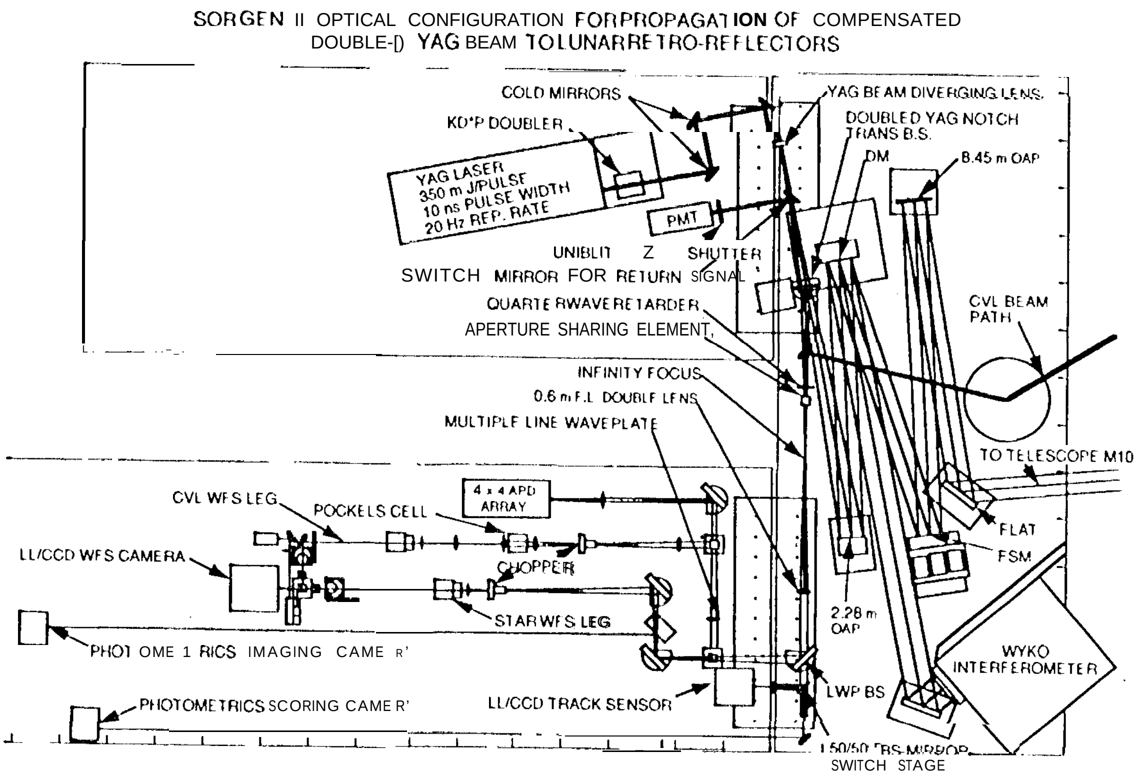

Figure 4. CEMERLL experimental setup at the SOR. The wavefronts of the Nd:YAG signal and the CVL guide star beam are preconditioned prior to coalignment at the doubled YAG notch transmission beam-splitter.

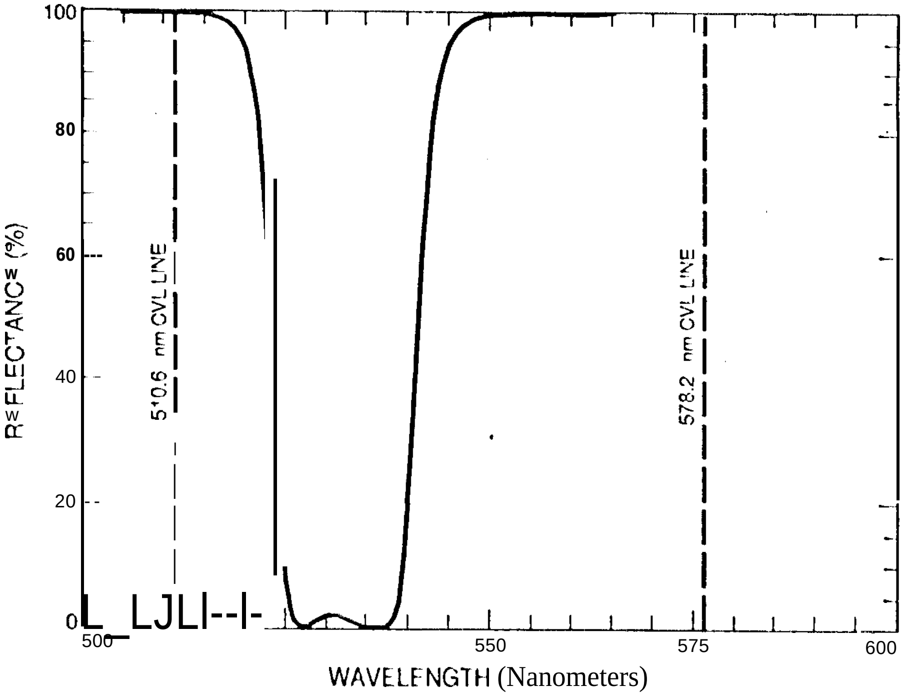

Figure 5. Transmission of the doubled YAG notch transmission filter. The two CVL lines at 510.6 nm and 578,2 nm are reflected by the beam-splitter, and the doubled YAG output transmitted.

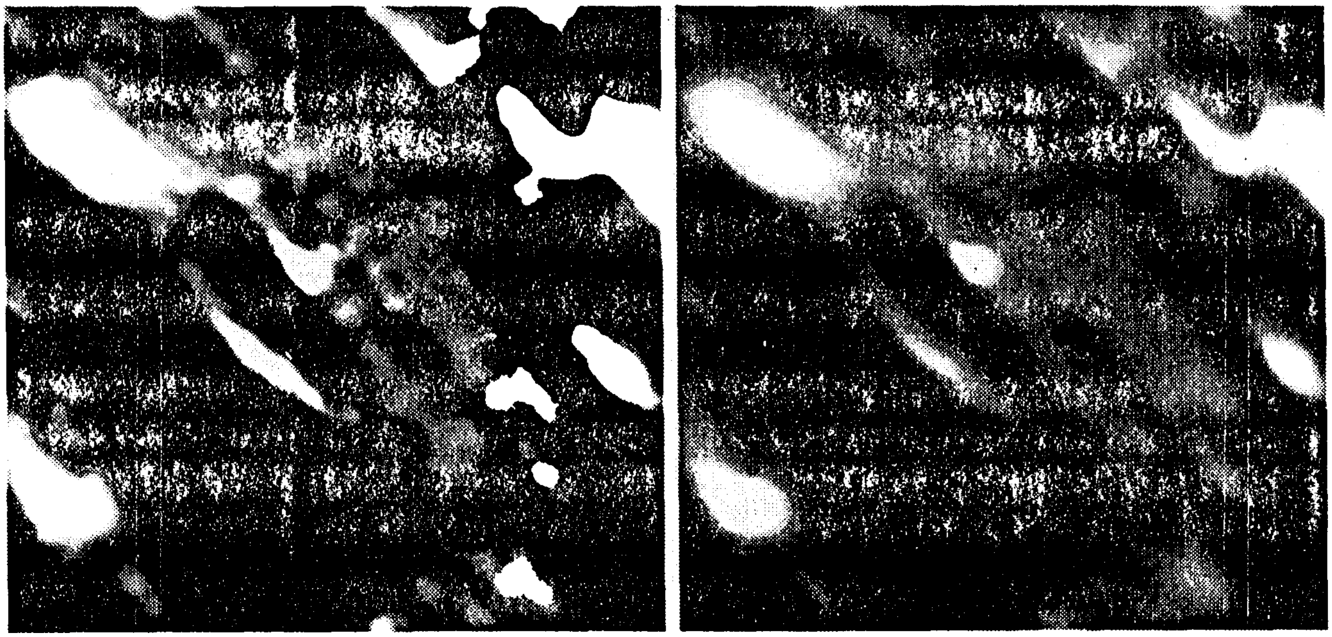

Figure 6. Images of the lunar surface near the Apollo retro-reflectors. These were made at the SOR with (left) and without (right) laser guide star adaptive optics compensation. With higher order wavefront distortions corrected by LGS-AO, significant enhancement in image contrast is achieved. (Courtesy of R.Q.Fugate, Director of Philips Laboratories' Starfire Optical Range.)